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Comparison of data for ozone amounts and ultraviolet doses obtained from simultaneous measurements with various standard ultraviolet instruments

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Abstract. Recent technological advances have made measurements of UV doses and ozone column amounts with multichannel filter instruments not only possible, but also an attractive alternative to other more labor-intensive and weather-dependent methods. Filter instruments can operate unattended for long periods of time, and it is possible to obtain accurate ozone column amounts even on cloudy days. We present results from extensive comparisons of the performance of several Norwegian Institute for Air Research UV (NILU-UV) and ground-based (GUV) filter instruments against Dobson and Brewer instruments and the earth probe–total ozone mapping spectrometer (EP-TOMS) instrument. The data used in the comparisons are from four different sites where we have had the opportunity to operate more than one type of UV instrument for extended periods of time. The sites include the University of Oslo, Norway; Ny-Alesund, Spitzbergen, Norway; the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center facilities at Wallops Island, Virginia, and Greenbelt, Maryland; and the University of Alaska, Fairbanks. Our results show that ozone column amounts obtained with current filter-type instruments have an accuracy similar to those obtained with the Dobson instrument. The mean difference between NILU-UV and Dobson direct sun measurements were $0.4 \pm 1.9\%$ (1σ) in Oslo for the period 2000 to 2003. The difference between a GUV and the same Dobson was $1.7 \pm 1.4\%$ for the same time period. The mean difference between GUV and TOMS in Ny-Alesund 79 deg N and Oslo 60 deg N in the period 1996 to 1999 was $< 0.5 \pm 3\%$ for days with noon solar zenith angles (SZAs) < 80 deg. *© 2005 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.1885473]

Subject terms: filter instruments; Dobson; Brewer; total ozone mapping spectrometer; ozone measurements; ultraviolet radiation; clouds.

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1 Introduction

Multichannel filter instruments have become popular recently and are now used in several national UV monitoring networks.[1] Multichannel filter radiometers have no moving parts, are easy to calibrate, and require little attention. The instruments are primarily designed to measure irradiances in a few channels in the UV and visible parts of the solar spectrum. However, a method for derivation of biologically weighted UV doses, cloud effects, and total ozone columns[2] makes the instruments more interesting and useful to the scientific community. The objective of this paper is to show that ozone columns derived from this type of instrument are accurate and that the influence of clouds on derived ozone column amounts is small. We used data from filter instruments at stations covering latitudes from 38 to 79 deg N and compared them with data from standard ozone instruments such as Brewer, Dobson, and the total ozone mapping spectrometer (TOMS) instrument aboard the Earth Probe satellite. We also discuss the solar zenith angle and ozone profile dependency on the derived ozone column amounts. Erythemal UV dose rates[3] measured with instruments from two different manufacturers are compared.

2 Methodology

The methodology for deriving UV doses, total ozone column amounts, and cloud effects are only briefly described

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here since details can be found elsewhere.[2] If $R_i'(\lambda)$ is the relative spectral response of channel *i*, the absolute responsivity $R_i(\lambda)$ is related to $R_i'(\lambda)$ by

$$R_i(\lambda)=k_i[R_i'(\lambda)]. \tag{1}$$

The raw signal from channel *i*, V_i, depends on the spectral irradiance of the radiation the instrument is exposed to, $F(\lambda)$, and the spectral response function:

$$V_i=\int_0^\infty k_i[R_i'(\lambda)][F(\lambda)]\mathrm{d}\lambda. \tag{2}$$

The k_i can be considered to be a calibration factor for channel *i*. This calibration factor is determined by exposing the instrument to a known source [i.e., a lamp traceable to the National Institute of Standards and Technology (NIST) or the sun]. Note $F(\lambda)$ was measured by a well-calibrated spectroradiometer. Once the calibration factor k_i is determined from Eq. (2), it can be used to simulate the output of channel *i* (i.e., the raw signal) for any given spectral irradiance $F(\lambda)$. All our filter instruments were calibrated against a double-monochromator Bentham spectroradiometer at the Norwegian Radiation Protection Authority with the sun as the radiation source and the relative spectral responses were measured in their calibration lab.[4] Note that only one single spectrum is required to perform the calibration.

Total ozone is determined by comparing a calculated and measured irradiance ratio

$$N(Z,\Omega)=\frac{V_i(Z,\Omega)}{V_j(Z,\Omega)}, \tag{3}$$

where *Z* is the solar zenith angle, Ω is the total ozone amount, and *i* and *j* refer to two channels with different ozone absorptions. A number of channel ratios can be used since we have four to five channels available. The calculations are based on a radiative transfer model,[5] where the curvature of the atmosphere is taken into account.[6] The calculations are done for clear-sky conditions only because the ratio is little affected by clouds.[2]

The influence of clouds on the measured irradiances can be described in terms of a ''cloud transmission factor'' (CLT). For a UV-A channel *j* that is weakly or unaffected by ozone absorption, we define CLT as

$$\mathrm{CLT}=\frac{V_i^{\mathrm{measured}}(Z)}{V_i^{\mathrm{calculated}}(Z)}. \tag{4}$$

The denominator in Eq. (4) is the calculated[2,5,6] clear-sky irradiance using Eq. (2) with no aerosols and zero surface albedo at solar zenith angle *Z*, and $V_i^{\mathrm{measured}}(Z)$ is the measured irradiance in channel *i* at solar zenith angle *Z*. The CLT is thus expected to be close to unity for a clean cloud-free atmosphere if the surface is not snow covered. In Oslo, we find that the CLT for a cloud-free sky is typically 95 to 100%. In other locations with heavier aerosol loading, the CLT value for a cloud-free sky value will be lower. CLT is used to filter out ozone measurements that are affected by clouds. Experience from measurements in Oslo since 1995 indicates that if the CLT>30%, the influence of clouds on the measured ozone column amount is negligible. The error in retrieved ozone due to clouds increases with surface albedo. Radiative transfer calculations[2] show that for a surface albedo of 0.8 and a cloud of optical depth 100 between 2 and 4 km, the retrieved ozone column is overestimated by ~6%. The reason for this larger error can be explained by multiple reflections between the cloud and the surface leading to increased path length for the photons and thus increased absorption.[2]

Table 1 Center wavelengths and bandwidths for NILU-UV and GUV when they are exposed to a solar spectrum at SZA=40 deg and ozone amount 320 Dobson units (DU).

	GUV		NILU-UV	
Channel No.	Center (nm)	Bandwidth (nm)	Center (nm)	Bandwidth (nm)
1	306	5	304	5
2	314	8	311	9
3	320	10	318	10
4	340	10	336	10
5	380	7	378	6

Biologically effective UV doses weighted with any action spectrum $A(\lambda)$ are determined by a weighted sum of the measured raw signals

$$D=\epsilon(Z,\Omega)\sum_{i=1}^{N} a_i V_i. \tag{5}$$

The a_is are coefficients that depend on the biological action spectrum chosen. The error function $\epsilon(z,\Omega)$ depends on solar zenith angle *Z* and the total ozone amount Ω. However, $\epsilon(z,\Omega)$ is normally close to unity.[2]

3 Instruments and Locations

The filter instruments we use consist of a ground-based UV (GUV) instrument (manufactured by Biospherical Instruments, San Diego, California, USA) and the Norwegian Institute for Air Research UV (NILU-UV) instrument (manufactured by NILU Products, Kjeller, Norway). The

Table 2 The instruments used in this paper and their locations.

Site	Latitude	Ozone Instruments
Oslo	60 deg N	Dobson, Brewer, 2 NILU-UVs, GUV
Ny-Ålesund	79 deg N	GUV
Wallops Island	38 deg N	Dobson, NILU-UV
Fairbanks	65 deg N	NILU-UV, 2 Dobsons

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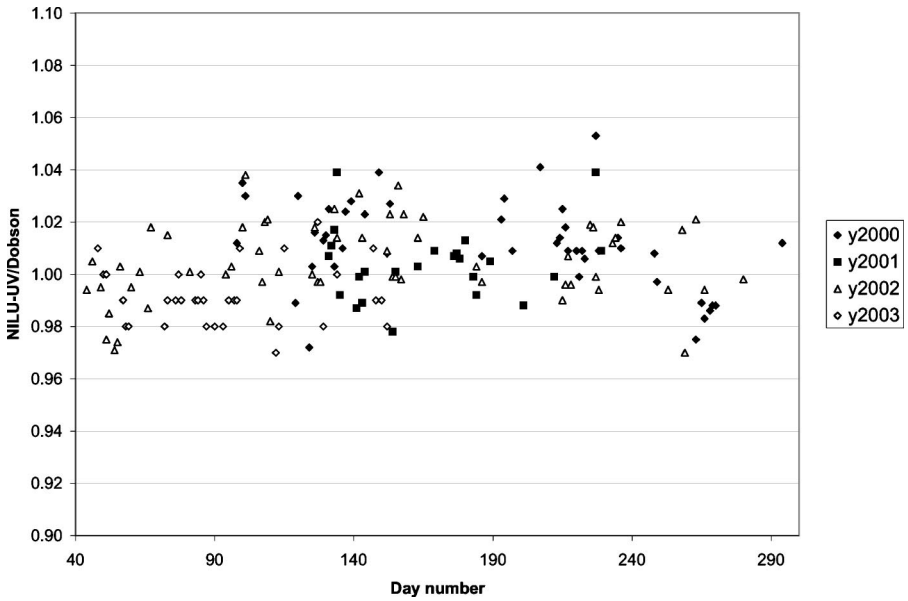

Fig. 1 Comparison of daily ozone measurements from NILU-UV 13 and Dobson 56 in Oslo for 2000 to 2003. The mean difference is 0.4±1.9%.

GUV and NILU-UV are equipped with four to five channels covering the UV and visible parts of the solar spectrum and having bandwidths of 5 to 10 nm FWHM (full width at half maximum), as shown in Table 1. The instruments are equipped with an internal heater and are stabilized to 40°C. The time resolution of the measurements is 1 min. Some of the instruments also have a photosynthetically active radiation (PAR) channel (400 to 700 nm), but this is not considered here. We define an effective center wavelength in a channel λ_c by

$$\lambda_c = \frac{\int_0^\infty \lambda R(\lambda) F(\lambda, Z, \Omega) \mathrm{d}\lambda}{\int_0^\infty R(\lambda) F(\lambda, Z, \Omega) \mathrm{d}\lambda}.$$

The center wavelength λ_c will generally vary with Z and for a UV-B channel also on the total ozone amount Ω. The values of λ_c and the corresponding bandwidths for 320 DU and a solar zenith angle (SZA) of 40 deg are shown in Table 1. An overview of the instruments and their locations are given in Table 2.

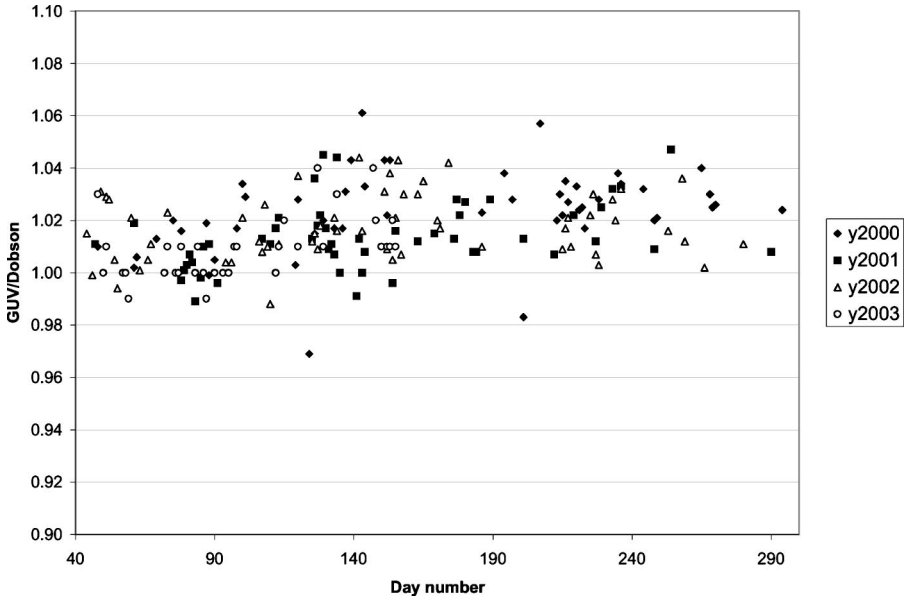

Fig. 2 Comparison of daily ozone measurements from GUV 9222 and Dobson 56 in Oslo for 2000 to 2003. The mean difference is 1.7±1.4%.

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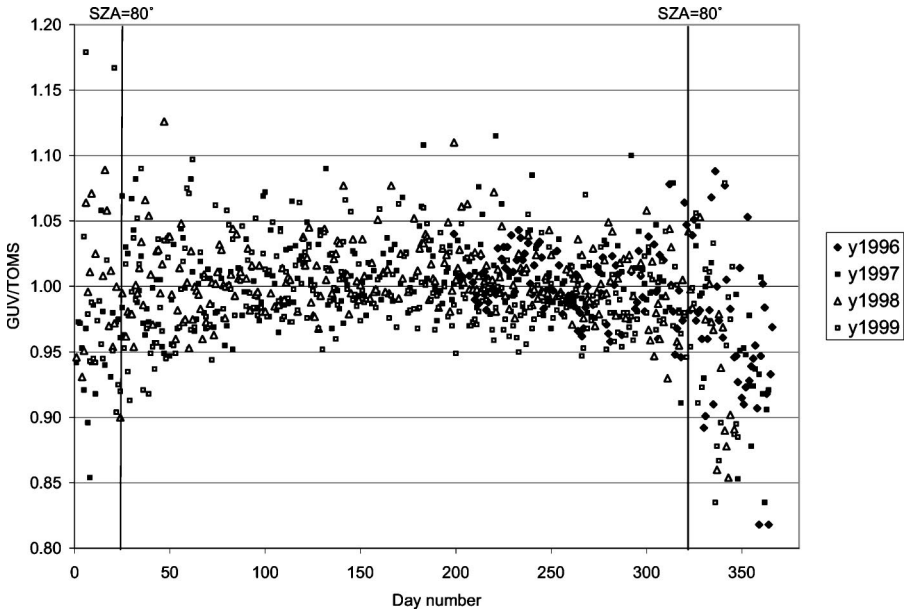

Fig. 3 Comparison of daily GUV and TOMS ozone measurements in Oslo for 1996 to 1999. Cloudy days (CLT>30%) are included.

4 Results

4.1 *Daily Ozone Measurements*

A comparison of daily total ozone measurements from NILU-UV 13 and direct sun measurements from Dobson 56 in Oslo for 2000 to 2003 is shown in Fig. 1. The distance between the instruments is approximately 20 km. The Dobson measurements are performed within 1 h from local solar noon and the NILU-UV measurements are based on a 1-h average around local solar noon (normally 60 single measurements). The mean difference (NILU-UV-Dobson)/Dobson for the 3-yr period is $0.4 \pm 1.9\%$ (1 standard deviation). A similar comparison for the Oslo GUV 9222 and the Dobson is shown in Fig. 2 for the same time period. The mean difference is $1.7 \pm 1.4\%$. No pronounced seasonal variations in the ratios are observed for the NILU-UV or the GUV.

The GUV instruments have been in continuous operation in Oslo and Ny-Ålesund, Spitzbergen, since 1995. Comparisons of ozone column amounts derived from these GUVs with satellite measurements from the Earth Probe TOMS instrument for 1996 to 1999 are shown in Figs. 3 and 4. The data contain cloudy as well as clear skies. In Oslo, for days 80 to 260 (which is the season when the

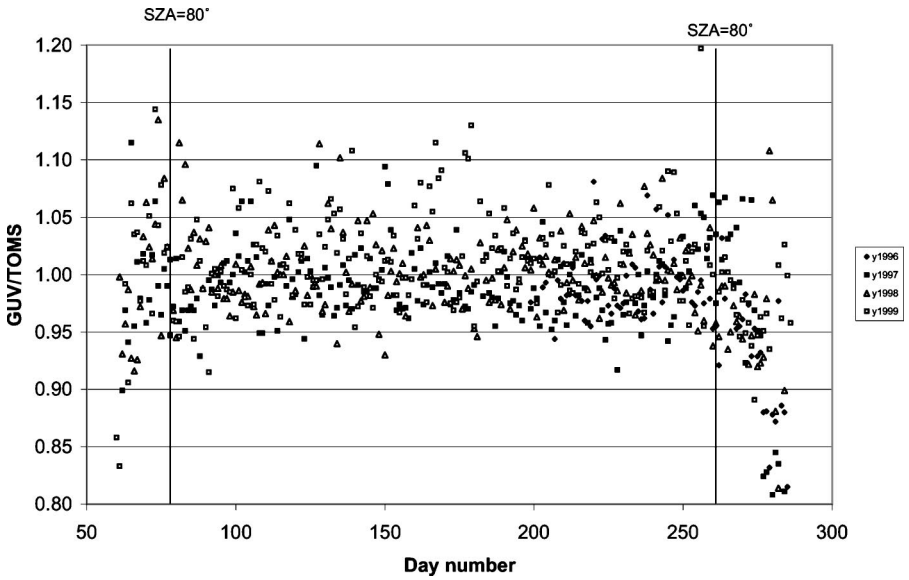

Fig. 4 Comparison of daily GUV and TOMS ozone in Ny-Ålesund for 1996 to 1999. Cloudy days (CLT>30%) are included.

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Table 3 Comparison of NILU-UV and GUV with Dobson and TOMS ($\pm 1\sigma$).

Site	NILU-UV/ Dobson[1]	GUV/ Dobson[1]	GUV/ TOMS[2]	GUV/ TOMS[3]
Oslo	1.004±0.019	1.017±0.014	1.002±0.032	1.000±0.025
Ny-Ålesund			1.001±0.033	1.004±0.033

[1]Dobson AD direct sun 2000 to 2003.

[2]Days with SZA<80 deg, cloudy days included (CLT>30%), 1996 to 1999.

[3]Days with SZA<60 deg, cloudy days (CLT>30%) are included, 1996 to 1999.

noon SZA is less than 60 deg) the relative difference is 0.0±2.5%. For the entire year, the difference is −0.4 ±3.9%, but this includes the 2-month period when the SZA at noon is larger than 80 deg and the column amounts derived from both instruments depend on the ozone profile. The relative difference for Ny-Ålesund for the period March 20 to September 20 when the SZA is less than 80 deg is 0.1±3.3%. As discussed in Secs. 2 and 4.2, ozone measurements in Oslo for which CLT<30% are sensitive to clouds, and these ozone measurements are therefore filtered out. The surface albedo at Ny-Ålesund is usually high most of the year. Thus, it is not obvious that the CLT criterion used to the Oslo data is suitable to the Ny-Ålesund data because the cloud effect increases with increasing surface albedo. However, a CLT<30% criterion is used also to the Ny-Ålesund data in Fig. 4, and we note that the agreement with TOMS is similar to the Oslo data in Fig. 3. A possible explanation is that the clouds are usually thin in the high-albedo season in Ny-Ålesund and therefore the cloud-albedo effect on the measured ozone columns amounts are rather small. The results of the comparisons of NILU-UV and GUV with Dobson and TOMS are shown in Table 3.

NILU-UV 21 was compared with two Dobson spectrophotometers in Fairbanks, Alaska, in a 2-week period in spring 2001. The NILU-UV agreed with Dobsons 63 and 83 within ±2% (Fig. 5). Another NILU-UV, 29, has been in continuous operation for about a year at Wallops Island, Virginia, USA, and has shown to be in excellent agreement with Dobson 38. One example is shown in Fig. 6, where both instruments show a large decrease on January 24, 2003.

A detailed comparison of Brewer 42 direct sun measurements and NILU-UV 13 measurements in Oslo, Norway, on day 197 is shown in Fig. 7. Both instruments show a steady increase in ozone from morning to evening. Also shown is the variation in CLT. Note that the NILU-UV ozone is very little affected by the changing cloud cover during the day.

4.2 *Cloud Effects*

Ozone column amounts derived from the GUV and NILU-UV instruments are nearly insensitive to clouds, if the cloud optical depth is below a certain value (or the cloud transmission CLT is above a certain value). Figure 8 shows how sensitive the measured ozone column amount is to CLT in the period of days 240 to 250, 2002, in Oslo. Each single 1-min-average ozone measurement from NILU-UV 13 is divided by the noon ozone value based on Brewer direct sun (ds in Fig. 8) measurements and plotted

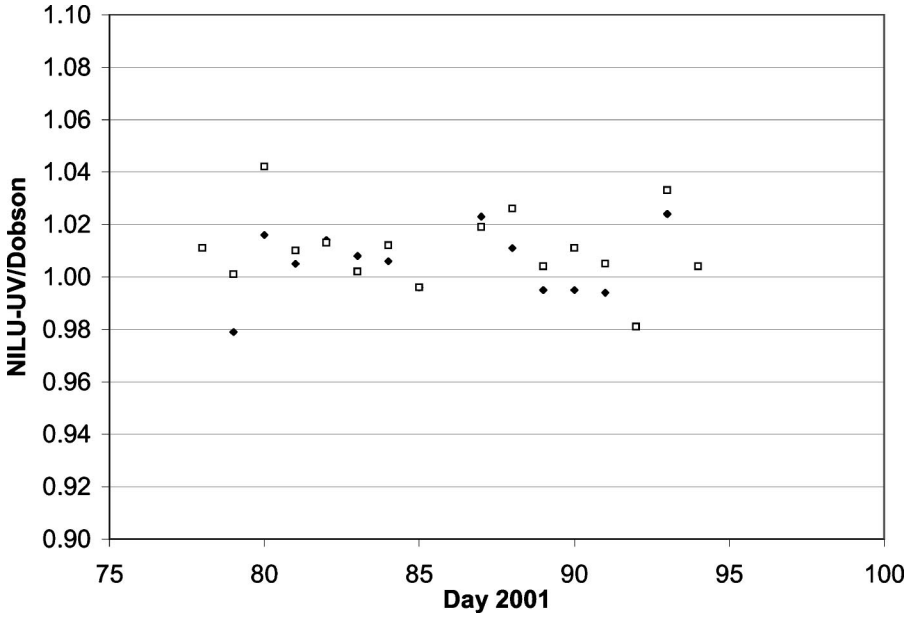

Fig. 5 Comparison of NILU-UV 21 with Dobsons 063 and 083 at Fairbanks, Alaska, 2001. NILU-UV 21/Dobson 063 (squares), NILU-UV 21/Dobson 083 (diamonds).

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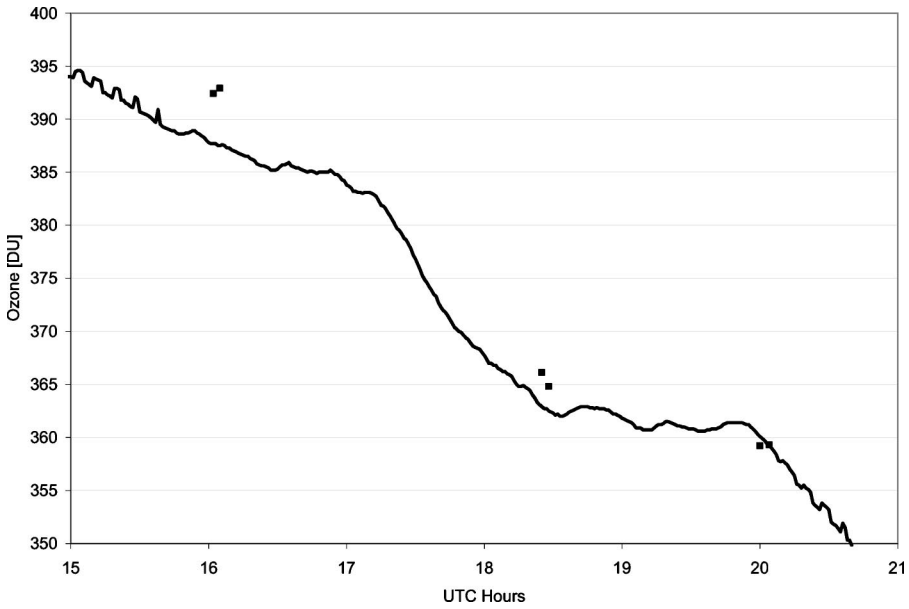

Fig. 6 Dobson (squares) and NILU-UV 29 (solid line) measurements at Wallops Island on day January 24, 2003. (Coordinated universal time: UTC).

as a function of CLT. Days 240 to 250 were chosen because this is a period with quite stable ozone layer (290 to 320 DU). Therefore, the deviation of the ratio from 1.0 in Fig. 8 should mainly be due to cloud cover. The ratio increases for CLTs below 30 to 40%, which means that the ozone column amount is overestimated. We conclude that if the CLT>30 to 40%, the influence of clouds on the measured ozone column amount is negligible. In the ozone comparisons presented in this paper, we used a 30% CLT criterion. In Oslo, more than 85% of the measurements in the period 1995 to 2003 had CLTs>30%.

4.3 *Sensitivity to Ozone Profile*

Ozone column amounts derived from the GUV and NILU-UV instruments are based on a comparison of a measured irradiance ratio with the same ratio computed with a radiative transfer model. To determine how sensitive the derived ozone column amount is to the ozone profile used in the model, we derived ozone column amounts from day 208 in 2002 in Oslo from GUV 9222 with three different model profiles: a low-latitude, a midlatitude, and a high-latitude ozone profile from TOMS version 7 ozone profile

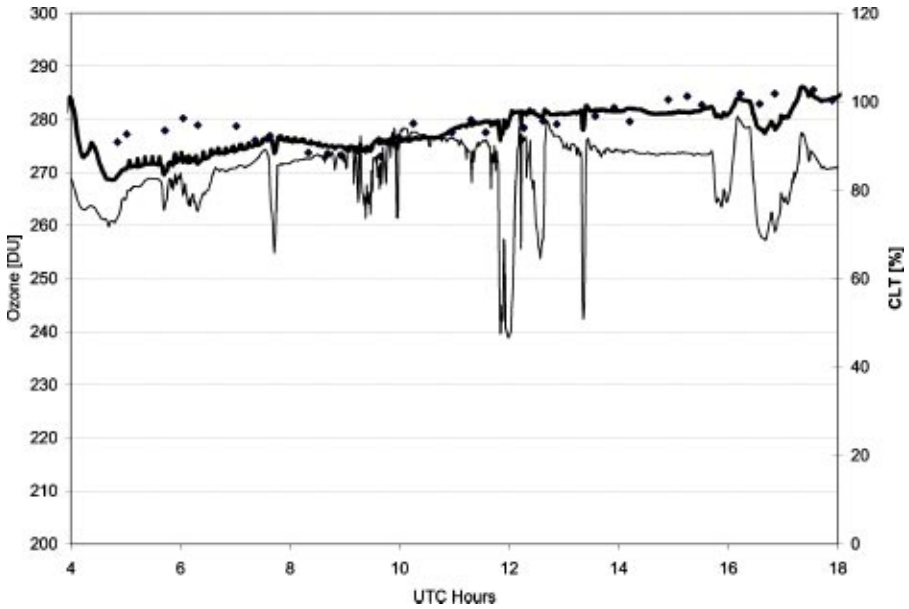

Fig. 7 NILU-UV 13 ozone measurements (thick solid line, left axis) and Brewer 042 measurements (diamonds) on day 197, 2002, in Oslo. The variation in cloud cover, CLT (right axis), is also shown (thin solid line). (Coordinated universal time: UTC).

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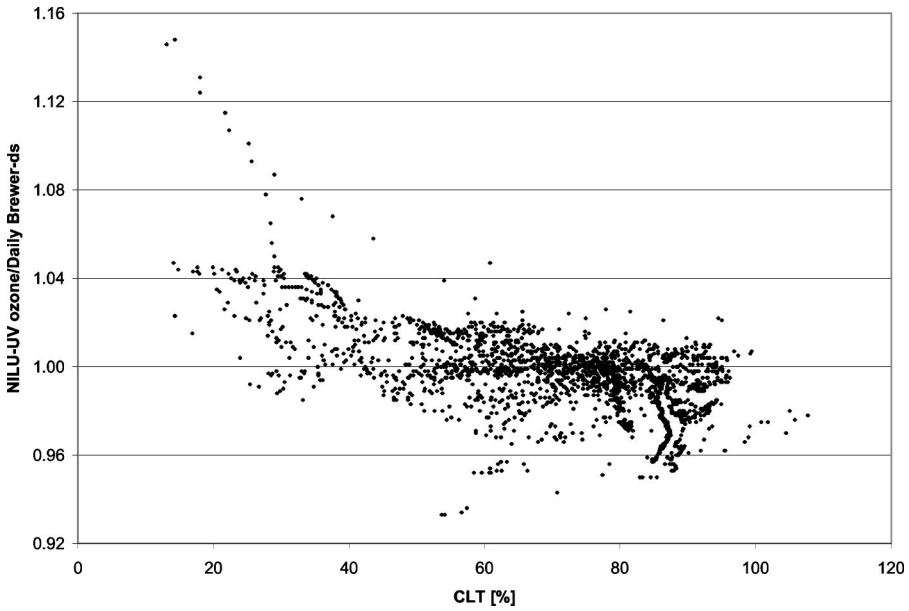

Fig. 8 Cloud effects on NILU-UV 13 ozone measurements in Oslo between day 240 and day 250 in 2002 (2500 single measurements). Only measurements with SZA<60 deg are included.

climatology. Figure 9 shows the ozone column amounts derived from the GUV with the low- and high-latitude profiles relative to that derived with the midlatitude profile as a function of SZA on day 208 in Oslo in 2002. An important result is that the measured ozone column amount is independent of the profile for SZA<65 deg. For large SZA values, the derived ozone column amount depends strongly on the ozone profile. This is a well-known effect that is used to derive ozone profiles from measurements of scattered solar UV radiation from the zenith direction.[7,8] The dependency of ozone profile on UV-B irradiances was discussed by Bruhl and Crutzen.[9] A shift of ozone from the stratosphere to the troposphere will lead to a decrease in surface UV-B irradiances. This is due to the relatively longer path length through the tropospheric than through the stratospheric ozone. The path length increase is caused by the relatively larger contribution of diffuse radiation in the troposphere compared to the stratosphere. This was further discussed by Tsay and Stamnes,[10] who noted that the diffuse radiation depends on two competing factors: (1) increased absorption by tropospheric ozone due to larger path lengths of photons in the troposphere and (2) enhancement of the source of diffuse radiation in the troposphere due to an increase in the direct beam radiation passing through the stratosphere. The first factor leads to a decrease in the diffuse radiation, the second to an increase. The latter factor

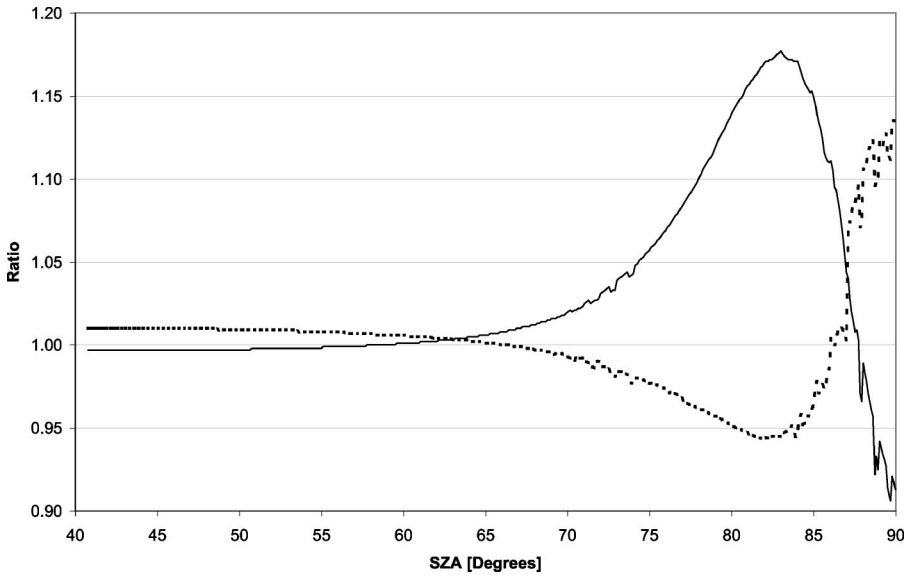

Fig. 9 Sensitivity to ozone profile on ozone derived from GUV 9222 on day 208 in Oslo in 2002: high-latitude profile relative to midlatitude profile (solid line), and low-latitude relative to mid-latitude profile (dashed line).

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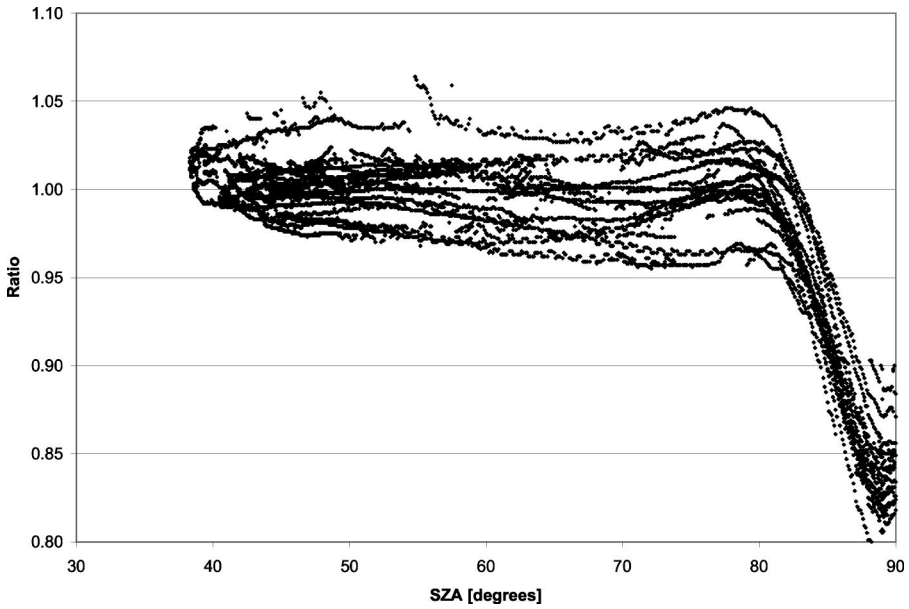

Fig. 10 SZA dependency on NILU-UV 13 ozone measurements in Oslo during days 190 to 220 of 2002 (8800 single ozone measurements).

depends strongly on the SZA, while the former does not. This explains why a high-latitude ozone profile gives more UV-B radiation at the surface than a low-latitude ozone profile for large SZAs and vice versa. However, the effect is very small for small SZAs, as demonstrated by Fig. 9.

4.4 *Solar Zenith Angle Dependency*

A high-quality ozone instrument should show no or only small SZA dependencies. Figure 10 shows each single-minute-average ozone measurement from NILU-UV 13 in Oslo divided by its corresponding Brewer direct sun noon value as a function of SZA for the period day 190 to day 220 in 2002. No obvious SZA dependency is observed for SZA$<$80 deg. The deviations from 1.0 seen in the figure (however, rather small) may partly be due to clouds and real changes in total ozone with time.

4.5 *Comparison of UV Dose Rates Measured by NILU-UV and GUV*

NILU-UV 13 is operated at NILU, Kjeller, and GUV 9222 is located 20 km away at the University of Oslo. Therefore a comparison of the two instruments is difficult unless the sky is clear at both sites. Figure 11 shows dose rates from both sites on day 187, 2002, which was clear. In Fig. 12, the ratio of Commission Internationale de l'Eclairage (CIE) dose rates (GUV/NILU-UV) for the same day as a function

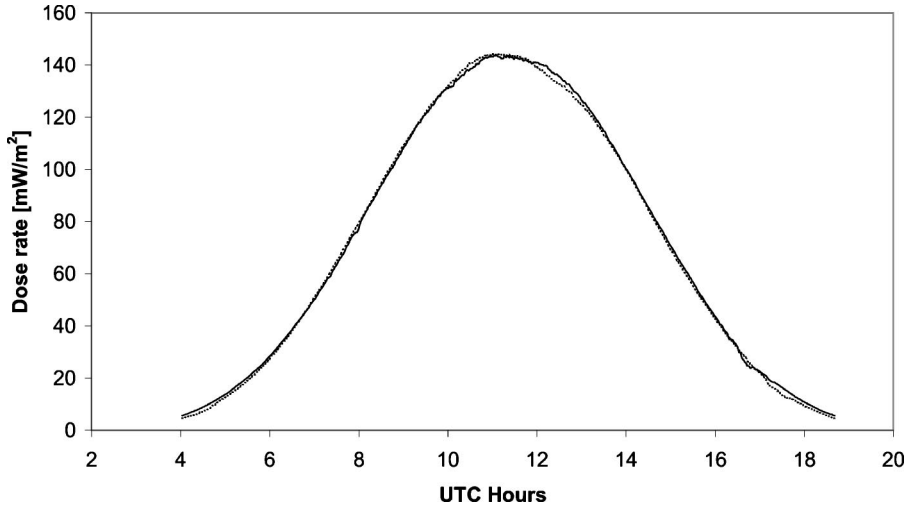

Fig. 11 CIE weighted UV dose rates measured by GUV 9222 at the University of Oslo, Norway (solid line), and NILU-UV 13 at NILU, Kjeller, Norway (dotted line), on day 187 of 2002. The distance between the GUV and the NILU-UV is 10 km. The sky was clear at both sites.

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Fig. 12 Ratio GUV/NILU-UV as a function of solar zenith angle for the data in Fig. 11.

of SZA is shown. The two instruments agree within ±2% for SZA<63 deg. The increasing deviation for larger SZAs may partly be due to different cosine responses. However, since the instruments are not located at the same site, the differences for large SZAs may partly be due to different local effects.

5 Conclusions

We have shown that total ozone column amounts derived from irradiance measurements with NILU-UV and GUV instruments are of high quality for clear as well as cloudy skies. The percentage differences between the filter instruments and the Dobsons were less than 2% and with standard deviations less than 2%. The cloud cover was described in terms of a cloud transmission factor, CLT, which is the ratio of irradiance from a UV-A channel to the corresponding clear-sky irradiance. The influence of clouds on ozone measurements with the filter instruments was found to be small for CLT>30 to 40%. In Oslo, more than 85% of the measurements in the period 1995 to 2003 had CLTs >30%. We found that the ozone measurements are insensitive to ozone profile for $SZA_{\circ}$<65 deg. At our high-latitude stations in Oslo and Ny-Alesund, we assumed the high-latitude ozone profile climatology, as used in the TOMS version 7 algorithm. This gave us reliable ozone data for SZA<80 deg. The stability of filter instruments seems to be variable. Some are very stable over years, while others start to drift without any clear reason. Like any instrument designed to measure ozone column amounts, frequent calibrations are required to detect any drift. This can be done with a traveling reference instrument or standard lamps. By correcting the data for the measured drift, the quality of the data is ensured.

Acknowledgments

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